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AUGMENTATION OF FREE SURFACE HEAT AND MASS TRANSFER DUE TO ELECTROSTATIC FIELDS

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ABSTRACT

Experiments were conducted to measure heat transfer rates and mass transfer rates from a water surface in the presence of electrostatic fields of various strengths generated between the water surface and a wire grid above the surface.

Heat transfer rates were determined by the temperature decay after heating the test and control basins. Mass transfer rates were determined by measuring the water loss while holding the basins at fixed temperatures.

It was found that very little increase in transfer coefficients took place for voltages below an onset voltage which depended on atmospheric conditions and test geometry. The heat transfer coefficient increased for voltages above the onset voltage reaching factors of three to four times the natural rate. The mass transfer coefficient also increased similar amounts for voltages above the onset voltage. The functional dependence of the increased heat and mass transfer rates on grid voltage agreed with theory developed for heat transfer from plates without mass transfer. Mass transfer could be predicted using the analogy of heat and mass transfer, but heat transfer could not because of the unknown contribution of radiative transfer which was not independently monitored.

NOMENCLATURE

Symbol	Definition
C_p	Specific heat at constant pressure
D	Spacing between wire and plate
E	Total mass flux
E_f	Free convection mass flux
E_c	Corona convection mass flux
e	Vapor pressure
g	Acceleration of gravity
h	Convective heat transfer coefficient
K_h	Overall heat transfer coefficient
K_{h_f}	Overall heat transfer coefficient free convection
K_{h_c}	Overall heat transfer coefficient, corona driven
K_m	Mass transfer coefficient
k	Thermal conductivity
L	Length
M	Molecular weight
P	Pressure
P_c	Corona power
R	Universal gas constant
T	Temperature
V	Voltage
V_o	Corona onset voltage

Greek Letters	Definition
α	Thermal diffusivity
β	Coefficient of thermal expansion
Δ	Difference
ϵ	permittivity
μ	Dynamic viscosity
ν	Kinematic viscosity
ρ	Density
ρ_v	Vapor density
ϕ	Heat flux

Subscripts

w.v.	Water vapor
s	Surface
a	Air
c	Corona

Dimensionless Groups

Gr	Grashof number = $g\beta L^3 \Delta T/\nu^2$
NU	Nusselt number = hL/k
Pr	Prandtl number = ν/α

INTRODUCTION

The augmentation of heat transfer in gases by electric fields has been under investigation since the early 1930's when it was first discovered that heat transfer rates may be substantially increased by the presence of an electric field (1). It was first thought that this increase was due to electrostrictive forces resulting from a variation in electrical properties of the gas caused by its nonuniform temperature. Recently, it has been found that the increase is due primarily to an ion-drag force or "corona wind" (2). If air is subjected to an electric field of less than 3000 kV/m, the electrons and ions that are present in air due to such effects as ultraviolet radiation and cosmic rays, will be set into motion by the field. If the field is increased to approximately 3000 kV/m, the ions will have enough energy to enable them to dislodge an electron in a collision with a neutral molecule within the field. These new positive ions and electrons are then accelerated by the field and may collide with other neutral molecules. If the electric field is uniform, such as between parallel plates, this will lead to an electrical breakdown and an arc will occur between the two electrodes (3). If, however, a cylindrical electrode, such as a wire, is used, the field will reach a critical value at the surface of the conductor first and the intensity of the field will decrease in inverse proportion to the distance from the center of the conductor (4). Thus, a region of sustained ionization will exist around the electrodes without a complete electrical breakdown. The voltage at which the corona just begins to form is known as the onset voltage or corona threshold voltage and is dependent upon the temperature and moisture content of the air, diameter and surface roughness of the electrode, and the spacing between electrodes.

When a corona was applied over a heated horizontal flat plate, it was found that there was an increase in heat transfer above that due to free convection (5) which was caused by changes in the motion of the air over the surface of the plate. In free convection, fluid motion is a result of the buoyancy forces on the fluid when the density near the surface of the plate is decreased as a result of heating. When an electric corona is applied over the surface, an increase in fluid motion results from the movement of ions within the electrical field and the neutral molecules with which they collide. This movement, due to corona wind, has been observed to create circulation cells in the fluid between the wire and the plate (6, 7).

If the flat plate is replaced by a water surface, an additional increase in heat transfer results from evaporative mass transfer. As with heat transfer, mass transfer may also be improved through additional fluid motion. Evaporation from the water surface causes the concentration of water vapor in the air above the surface to increase. Vapor is removed from the vicinity of the surface by diffusion and convection (8). Application of an electric corona above the water surface produces a corona wind which aids the removal of vapor from the vicinity of the water surface and increases the mass transfer rate by evaporation.

Most of the work performed to date with regard to electrically enhanced mass transfer has dealt with the condensation of a vapor in a closed system. This paper examines the influence of electric fields on heat and mass transfer from a heated water surface into air by free convection.

APPARATUS AND PROCEDURE

Heat transfer rates were measured using a cylindrical test basin of approximately 0.5 m^2 surface area 5 cm deep (9). The test basin, Figure 1, and an identical control basin were constructed from PVC plastic and insulated with polystyrene foam. Heated tap water was added to the basins prior to each test. A wire grid supported by an acrylic frame, Figure 2, was placed over the test basin and leveled. The wire grid consisted of 0.178 mm diameter stainless steel wire strung through six radial arms of the acrylic frame nominally 2.9 cm above the water surface. The wires formed eight concentric hexagonal rings whose spacing increased radially so that the area between all concentric rings was equal. Testing was begun by applying a high DC voltage to the grid from a 50 kilovolt, one-half milliamp electronic power supply, Figure 3. A bare conductor on the basin bottom formed a ground connection. During the one hour test period, the water temperature was continuously monitored by a temperature recorder connected to thermocouples mounted inside the test basin. The one hour test period provided sufficient temperature decay to determine heat transfer at several temperatures. The

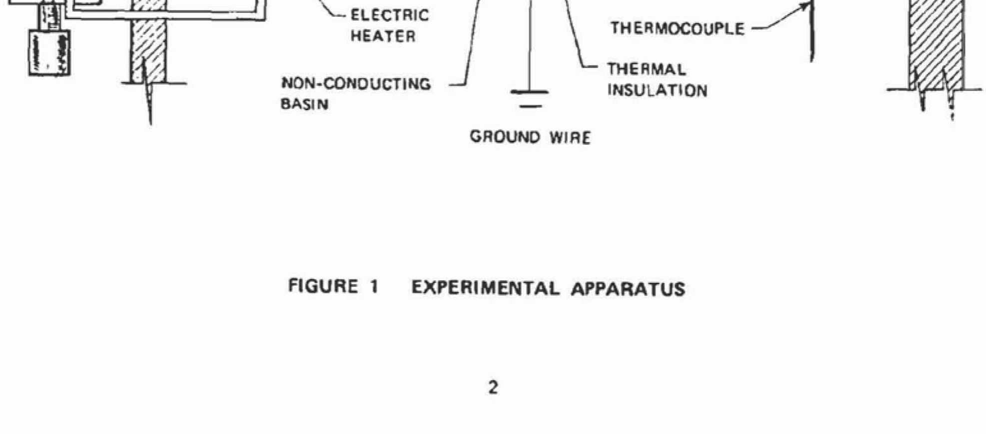

FIGURE 1 EXPERIMENTAL APPARATUS

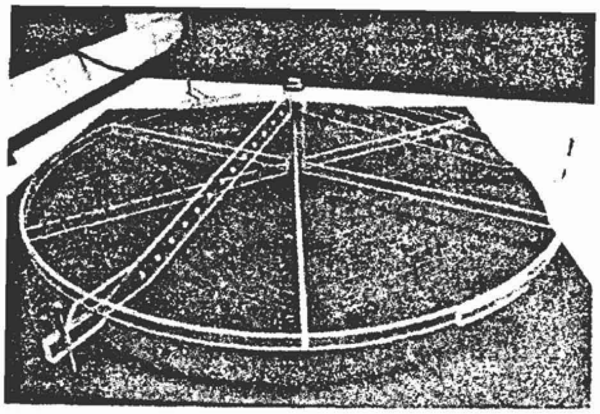

FIGURE 2 HEXAGONAL WIRE GRID

wet and dry bulb temperature of the air, barometric pressure, and corona current were also recorded during tests. The temperature decay in the test basin was then compared against the control basin and the information used to determine the degree of enhancement in the rate of heat transfer due to the electric field. The tests were then repeated at several grid voltages.

The mass transfer rate was determined by measuring the change in the water level in a test basin similar to that used for heat transfer measurements but designed to minimize volume change with temperature (8). Prior to testing the water was heated to 38°C by an electric heater in the basin, and maintained at that temperature during all tests. The initial water level in the basin was read by means of a Hook gage mounted aside of the basin and connected through a length of plastic tubing. The DC voltage was then applied to the same hexagonal grid 3.8 cm above the water surface for a period of one hour. During testing the wet and dry bulb temperature of the air, barometric pressure, and corona current were recorded. At the end of the one hour test, the final water level was read. The results were then compared against the control basin to determine the influence of the electric field on the mass transfer rate. Make up water was then added to the basin and the tests repeated at different grid voltages.

All tests were conducted indoors under ambient conditions. The dry bulb temperature was nominally 17°C, the wet bulb temperature varied from 10 to 16°C, and the barometric pressure was nominally 740 mm Hg.

THEORY

The expression for the total convective heat and mass transfer rates will be considered to consist of two parts. The first is that portion due to free convection that is dependent only on atmospheric conditions and the water properties. The second, which will be referred to as the corona convection rate, is that portion which is due to the effects of the electric corona.

The expression for the heat and mass transfer rates from the water surface will be found through analogy with free convective heat transfer from a heated flat plate. The approach was used by Ryan, Harleman, and Stolzenbach (10) and was found to give good results for artificially heated water surfaces in the laboratory.

The average free convection heat transfer coefficient may be represented in the following functional form:

$$NU = C\ (Gr,\ Pr)^m \qquad (1)$$

It has been found that for the case of a heated horizontal flat plate facing upward, C has the value of 0.14, and m the value of 1/3, when the product of the Grashof number and Prandtl number is greater than $5 \times 10^8 - 10^9$ as was the case here.

Through the definition of thermal diffusivity and the heat transfer coefficient

$$\alpha = \frac{k}{\rho C_p} \qquad (2)$$

$$h = \frac{\emptyset}{\Delta T} \qquad (3)$$

The Nusselt number may be expressed as

$$NU = \frac{\emptyset L}{\rho C_p \alpha \Delta T} \qquad (4)$$

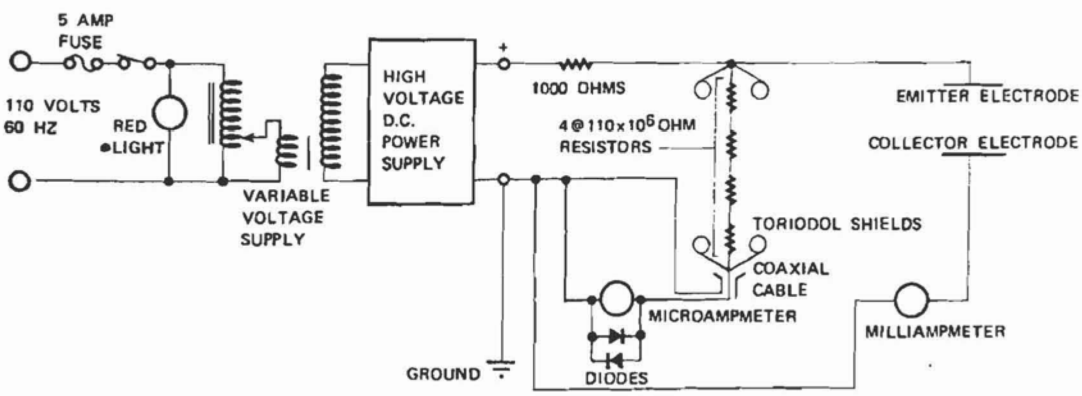

FIGURE 3 CIRCUIT SCHEMATIC

so that Eq. (1) then may be expressed as

$$\frac{\phi L}{\rho C_p \alpha \Delta T} = 0.14 \left(\frac{g\beta L^3 \Delta T}{\nu\alpha}\right)^{1/3} \quad (5)$$

and, solving, the heat flux ϕ is

$$\phi = 0.14 \rho C_p \left[g\beta\alpha^2 \Delta T/\nu\right]^{1/3} \Delta T \quad (6)$$

The heat transfer coefficient is defined as

$$K_h = \frac{\phi}{\rho C_p \Delta T} \quad (7)$$

substituting Eq. (6) into Eq. (7), the expression for free convection is

$$K_{hf} = 0.14 \left[\frac{g\beta\alpha^2 \Delta T}{\nu}\right]^{1/3} \quad (8)$$

Ryan et al. (10) assumed that the kinematic heat transfer coefficient is approximately equal to the mass transfer coefficient. The free convective mass flux may be expressed as (10, 11)

$$E = K_m (\rho_{vs} - \rho_{va}) \quad (9)$$

where

ρ_{vs} = water vapor density at the water surface
ρ_{va} = water vapor density in the ambient air
K_m = kinematic mass transfer coefficient

The vapor density may be related to the vapor pressure through the ideal gas law. Using the subscript f to denote free convection, Eq. (9) may be expressed as

$$E_f = 0.14 \frac{M_{wv}}{RT} \left[\frac{g\beta\alpha^2 (T_s - T_a)}{\nu}\right]^{1/3} (e_s - e_a) \quad (10)$$

The temperature of the water vapor in the air is assumed to be at the same temperature as the ambient air, therefore:

$$(RT)_{air} = (RT)_{wv} = \frac{P_a M_a}{\rho_a} \quad (11)$$

also

$$\frac{M_{wv}}{M_{air}} = 0.622 \quad (12)$$

Substituting Eqs. (11) and (12) into Eq. (10):

$$E_f = 0.14 \frac{0.622 \rho_a}{P_a} \left[\frac{g\beta\alpha^2 (T_s - T_a)}{\nu}\right]^{1/3} (e_s - e_a) \quad (13)$$

From Eq. (13) an estimate of the free convection mass transfer rate may be found if the air and water properties are known.

The corona driven convection terms can be found through a similar analogy to heat transfer from a heated flat plate. Mitchell and Williams (5) found through dimensional analysis that the functional relationship for a horizontal, heated flat plate facing upward cooled by a corona wind impinging down onto the surface may be expressed as:

$$NU = 3.82 Pr^{1/3} \left(\frac{L}{D}\right)^{0.496} \left[\frac{(V-V_o)^2 \rho\varepsilon}{\mu^2}\right]^{0.216} \quad (14)$$

Using the expression for Nusselt number given in Eq. (4), Eq. (14) may be rewritten as

$$\frac{\phi L}{\rho C_p \alpha \Delta T} = 3.82 (\nu/\alpha)^{1/3} \left(\frac{L}{D}\right)^{0.496} \left[\frac{(V-V_o)^2 \rho\varepsilon}{\mu^2}\right]^{0.216} \quad (15)$$

solving for $\phi/\rho C_p \Delta T$ the heat transfer coefficient K_h [Eq. (7)]

$$K_{hc} = 3.82 \frac{\rho^{0.216} \alpha^{2/3} \nu^{1/3}}{L^{0.504} D^{0.496}} \left[\frac{(V-V_o)^2 \varepsilon}{\mu^2}\right]^{0.216} \quad (16)$$

The expression for the mass flux is given by Eq. (9) combined with the ideal gas law gives

$$E = \frac{0.622 \rho_a}{P_a} K_m (e_s - e_a) \quad (17)$$

If the heat and mass transfer coefficients are assumed to be approximately equal, Eq. (17) may be written to express the mass flux due to the corona

$$E_c = 2.376 \frac{\rho_a^{1.216} \alpha^{2/3} \nu^{1/3}}{P_a L^{0.504} D^{0.496}} \left[\frac{(V-V_o)^2 \varepsilon}{\mu^2}\right]^{0.216} (e_s - e_a) \quad (18)$$

This analysis for the mass transfer rates assumes that free evaporation occurs until the corona driven convection begins and dominates the process. A parallel analysis could be developed for the heat transfer which would include corona driven convection, latent heat exchange, and radiative transfer. This approach was, in fact, attempted, but ambiguity in evaluating the radiative exchange precluded systematic agreement with the measurements.

RESULTS

Overall heat transfer coefficients were calculated for both the test and control basins from the experimental data obtained in the heat transfer tests. Since the atmospheric conditions and water properties for both basins was the same, the only difference in the overall heat transfer coefficient should be due to the corona convection. Figure 4 shows the ratio of the overall heat transfer coefficient in the test basin to that in the control basin plotted as a function of the corona voltage for a water surface temperature of 41°C. To determine the corona voltage, the onset voltage was first determined by plotting the square root of the corona current against the grid voltage, Figure 5. The onset voltage is that voltage at which the line intercepts the axis. The corona voltage is the difference between the grid and onset voltages.

Similarly, the experimental data from the mass transfer tests was used to calculate mass transfer rates for both the test and control basins. Figure 6 shows the ratio of the mass transfer rate in the test basin to that in the control basin plotted as a function of corona voltage for a water surface temperature of 38°C. The threshold voltage determination is shown in Figure 7.

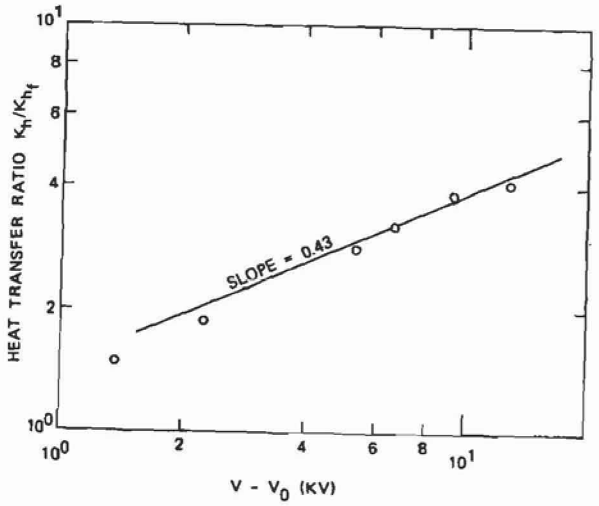

FIGURE 4 HEAT TRANSFER RATIO VERSUS CORONA VOLTAGE
(UNCERTAINTY IN K_h/K_{h_f} = ±0.45, V - V_0 = ±0.12 KV at 20:1 ODDS)

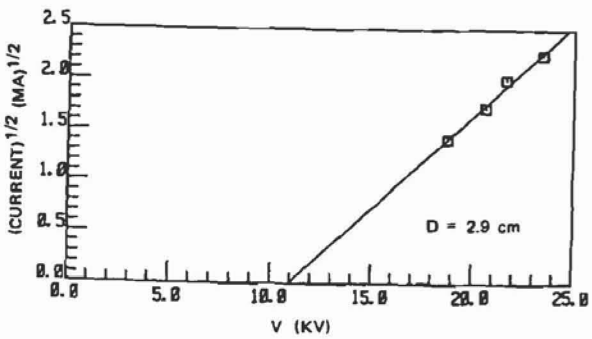

FIGURE 5 DETERMINATION OF ONSET VOLTAGE
(UNCERTAINTY IN CURRENT = ±0.22ma$^{1/2}$, V = ±0.12 KV at 20:1 ODDS)

For both the heat and mass transfer tests, most of the data was along a line whose slope was approximately 0.43 on a logarithmic plot. This suggests that the increase due to corona convection varies with approximately the 0.43 power of corona voltage, and is in agreement with the relations developed earlier, Eqs. (16) and (18). Eq. 18 is plotted in Figure 6 when the control basin evaporation rate was used for E_f and average ambient conditions were utilized. The good agreement with the measurements at higher voltage levels supports the idea that the corona driven air flow dominates the convection process.

The scatter in the data at the lower corona voltage in the mass transfer plot, Figure 6, is probably due to the transition from free to corona driven convection over the test basin. It was observed, however, that the electric field caused surface waves to form on the water surface and that the basin remained well mixed indicating that a flow field was established in the water as well as in the air. Alternatively, the control basin may not have been as well mixed as the test basin, not having benefit of additional driving forces.

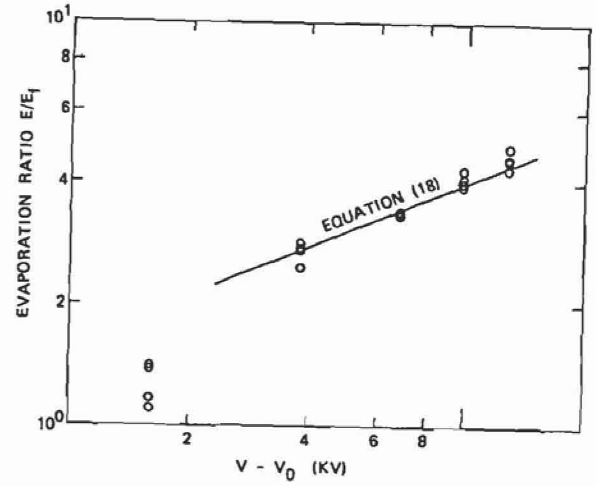

FIGURE 6 MASS TRANSFER RATIO VERSUS CORONA VOLTAGE
(UNCERTAINTY IN E/E_f = ±0.50, V - V_0 = ±0.12 KV AT 20:1 ODDS)

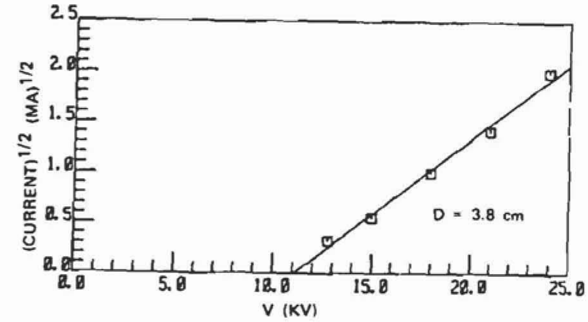

FIGURE 7 DETERMINATION OF ONSET VOLTAGE
(UNCERTAINTY IN CURRENT = ±0.22 ma$^{1/2}$ V = ±0.12 KV AT 20:1 ODDS)

DISCUSSION

The results of the tests conducted indicate that a substantial increase in the heat and mass transfer rate from a water surface may be gained through the use of an electric corona. Although this increase could probably have been obtained by using more conventional means, such as blowing, the use of an electric corona may be advantageous in some situations.

It was found through testing that the electric corona could be most efficiently utilized by attempting to evenly distribute the corona over the water surface. By observing the corona in the dark, it was discovered that the corona was strongest at certain bends in the hexagonal grid. Another grid consisting of straight wires was constructed and tested to determine if elimination of these zones of concentrated corona could improve the results. It was found that although the total rate of mass transfer was not significantly increased, the amount of power required to obtain the same degree of enhancement was slightly reduced. Although no tests were conducted to determine heat transfer rates with the straight wire grid, a similar result would most likely be obtained. Since the current to individual grid wires was not monitored or controlled, a less than optimum field strength distribution probably existed. Further enhancement could probably be achieved with such control. In addition, improvements in the field could possibly be obtained by using sharp points such as needles in place of wires since the corona is known to more easily form around such points.

CONCLUSIONS

The results of the tests conducted indicate that the heat and mass transfer rates from a heated water surface into still air may be significantly increased above the natural convection rate through the use of an electric field. The increase appears to be related to approximately the 0.43 power of the difference between the corona voltage and onset voltage, which is in agreement with relations developed through analogy with heat transfer from a heated horizontal flat plate. The evaporation measurements were predicted satisfactorily using the analogy. Ambiguity in determining radiative heat transfer precluded such comparison with the heat transfer data.

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